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How Spacecraft Will Communicate "on the Fly"

The Hi-DSN ad-hoc network infrastructure connects different kinds of spacecraft, supporting high-rate communications for mobile nodes

As NASA probes deeper into space, the distance between sensor and scientist increases, as does the time delay. NASA needs to close that gap, while integrating more spacecraft types and missions—from near-Earth orbit to deep space. To speed and integrate communications from space missions to scientists on Earth and back again, NASA needs a comprehensive, high-performance communications network. To this end, the CICT Program's Space Communications (SC) Project is providing technologies for building the Space Internet, which will consist of large backbone networks, mid-size access networks linked to the backbones, and smaller, ad-hoc networks linked to the access networks. A key component will be mobile, wireless networks for spacecraft flying in different configurations.

An adaptable infrastructure

David Foltz, manager of the SC Project's Interspacecraft Networks subproject, says, "NASA's observation missions are evolving from using single spacecraft to using multiple distributed spacecraft, including the International Space Station, the Space Shuttle, Earth-observation satellites, planetary orbiters, low-flying probes, and mobile surface rovers. This array of spacecraft with different capabilities will be positioned in shifting configurations that require an adaptable network architecture. As a first step, BBN Technologies in Cambridge, MA, with a team led by Marcos Bergamo, has been contracted by the SC Project to develop the adaptable communications network."

"How we design a spacecraft network depends on the mission and the types of spacecraft being deployed," says Bergamo. "Our challenge is to design a communications infrastructure that accommodates a wide range of missions, from civil aviation to the exploration of Mars, and different kinds of spacecraft, from orbiting satellites to aircraft and terminals on the ground. To meet this challenge, we designed the High-Throughput Distributed Spacecraft Network, or Hi-DSN. It provides an integrated set of radio transceiver capabilities and network protocols for establishing and maintaining communications among diverse spacecraft in multiple orbits, and for connecting them to aircraft and ground-based terminals."

Meeting multiple challenges

Many spacecraft networks will evolve over time, incorporating "newcomers" with different capabilities. Configurations can range from fixed formations (for large-scale telescopes) to orbiting constellations, clusters and sensor webs. These fluctuating configurations require ad-hoc networking capabilities that enable spacecraft (or nodes) to autonomously "discover" their "neighbors" and communicate directly with

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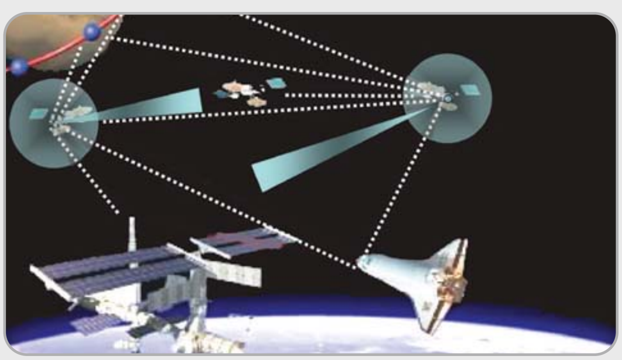

Hi-DSN will enable spacecraft of different types and capabilities to track each other's moving location, form an ad-hoc network, and communicate among themselves and with other parts of the Space Internet, including Earth.

Technology Spotlight

Technology

High-Throughput Distributed Spacecraft Network (Hi-DSN)

Function

Provides an ad-hoc communications infrastructure for a wide range of missions and spacecraft configurations

Relevant Conceptual Missions

- The integration of various missions to share their sensors, data, and communications
- Formation missions such as Leonardo (Earth Science Enterprise)

Applications

- Communications with ground terminals, planet rovers, low-flying probes
- Inter-spacecraft networking for formations, clusters, and constellations

Features

- Simultaneous recognition of newcomers and tracking of neighbors
- Simultaneous transmission/reception of multiple messages at different rates and modulations
- Dynamic null-beam steering
- Integrated time-, code-, and space-division multiplexing technology
- Multi-hop routing

Benefits

- Supports real-time applications
- Delivers optimal aggregate data throughput
- Offers maximum efficiency with minimal interference
- Supports multiple self-forming topologies for spacecraft of different capabilities, speeds, distances

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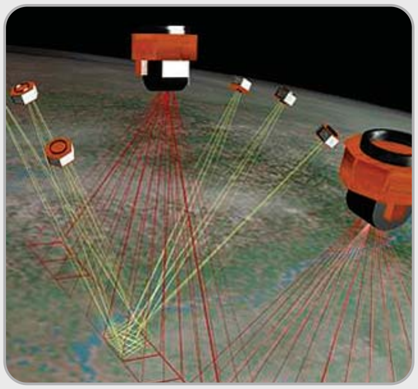

Hi-DSN may enable conceptual Earth Science missions, such as Leonardo (above), to become real. A system of small satellites would fly in formation, observing the same target from different directions. Hi-DSN could also be used to connect spacecraft from disparate missions into ad-hoc sensor webs, or into ad-hoc networks for routing data more quickly to Earth.

them or indirectly through them to other spacecraft beyond their range. In the latter instance, a source node's message to a destination node may "hop" from one intermediate node to another ("multi-hop" routing). If a node is in the path of multiple messages, it must simultaneously receive them at different speeds (because of varying distances) and either consume them (as the destination node) or re-transmit them (as relay node) in different forms (because of varying capabilities among nodes). Each node must also avoid interfering with messages from other nodes.

"We designed Hi-DSN to handle the most demanding problems, focusing on heterogeneity, flexibility, and high throughput," says Bergamo. "Hi-DSN is a scalable architecture, capable of self-formation with minimal information about all nodes. As it learns more, it optimizes its performance. Hi-DSN not only supports many possible configurations and nodes, but also the different distances, velocities, traffic mixes, and data rates of those nodes. It also supports more simple configurations and protocols."

Dynamic null-beam steering

Hi-DSN employs small, low-power, "smart" phase-array antennas that transmit focused beams at their target, while simultaneously pointing "nulls" at non-targeted spacecraft in the network to prevent interference. This "dynamic null-beam steering" enables a node to use (and re-use) the maximum available bandwidth to discover new neighbors and transmit and receive multiple messages at the maximum aggregate data rate.

Maximum multiplexing

Hi-DSN supports access to transmission and reception channels via a novel BBN-developed multiplexing technology, called TCeMA (TDMA with CDMA-encoding Multiple Access). TCeMA integrates the standard technologies for wireless communications—Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA)—with Spatial Division Multiple Access (SDMA). TDMA organizes messages by time, CDMA by code, and SDMA by spacing beam widths to avoid interference. TCeMA enables spacecraft to transmit and receive information simultaneously to and from many nodes at different rates and with different modulations, while keeping signals and amplifiers at constant power for maximum aggregate throughput and efficiency.

Simultaneously tracking all neighbors

The spacecraft use the Hi-DSN message-frame structure to learn each other's orbital parameters; measure and track relative angular directions, distances and velocities; and re-synchronize their internal clocks to the clock of a reference spacecraft. The Hi-DSN integrated time-code-space multiplexing ensures simultaneous, interference-free transmissions, regardless of the nodes' relative locations. Nodes can "capture" incoming signals as they arrive simultaneously from all neighbors in range, and then separate and detect the individual signals. To simultaneously track all satellites in the network, each spacecraft transmits beams of different power for range and different width (and gain) for coverage, in order to accommodate the relative positions and movement of other spacecraft.

"The relative distance and mobility of spacecraft on a planetary observation mission can fluctuate dramatically," says Bergamo. "Close to the equator the distances between them are relatively large—from hundreds to thousands of kilometers—and their mobility relatively small. Close to the poles, however, they tend to bunch together; the distances between spacecraft in different orbits are relative small (possibly less than 100 km), while their relative mobility is high. Hi-DSN tracks and accommodates all of these changing relationships."

Putting it to the test

Bergamo's team at BBN has already demonstrated the Hi-DSN architecture in action using laboratory prototypes and OPNET simulation. The laboratory prototype enabled network designers to evaluate how the modulation, encoding, and multiplexing technologies of TCeMA perform under extreme differences of distance (attenuation) and synchronization (frequencies and delays) between space links. The OPNET simulation enables them to evaluate how the higher-level protocols will scale to large networks.

"Hi-DSN will be a key enabler for self-forming, router-based networks in space," says Jeff Hayden. "It will enable different spacecraft to form ad-hoc sensor webs or communications networks for routing data more quickly to Earth. For example, data from infrared sensors could be combined with data from optical sensors to provide fighters of forest fires on Earth with life-saving information more quickly. Hi-DSN will be another key component of the emerging Space Internet, supporting both Earth and Deep Space applications."

–Larry Laufenberg

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